INL/CON-06-11873
PREPRINT

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IAN 2006

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August 2007

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Abstract

The Idaho National Laboratory, in collaboration with Idaho State University's Idaho Accelerator Center and the Los Alamos National Laboratory, continues to develop the Pulsed Photonuclear Assessment (PPA) technique for shielded nuclear material detection in large volume configurations, such as cargo containers. In recent years, the Department of Homeland Security has supported the development of a prototype PPA cargo inspection system. This PPA system integrates novel neutron and gamma-ray detectors for nuclear material detection along with a complementary and unique gray-scale, density mapping component for significant shield material detection. This paper will present the developmental status of the prototype system, its detection performance using several INL Calibration Pallets, and planned enhancements to further increase its nuclear material detection capability.

Keywords: photonuclear, cargo inspection, nuclear material detection

1. Introduction

For over a decade Idaho National Laboratory (INL), in conjunction with Idaho State University's Idaho Accelerator Center (IAC) and Los Alamos National Laboratory (LANL), has been developing active interrogation systems based on photonuclear techniques for a variety of inspection applications.[1-3] Through the sponsorship of the Department of Energy's Office of Nonproliferation and National Security (NA22), the Department of Homeland Security (DHS) and most recently DHS's Domestic Nuclear Detection Office (DNDO), the photon-based interrogation methodology has been developed into a prototype, field-deployable system that can identify shielded nuclear material in an array of different cargo containers. The prototype Pulsed Photonuclear Assessment (PPA) inspection technology uses pulsed, accelerator-generated, energetic photons to induce photofissions (and neutron-induced fissions) in shielded nuclear materials. Customized neutron and gamma-ray detectors monitor the induced radiation for specific time- and energy-dependent signatures indicating the presence of nuclear material. Additionally, the system utilizes a Grayscale Density Mapping (GSDM) system which can detect high-density (or significant quantities of low-density) shielding materials in cargo loadings. The PPA system has successfully demonstrated the ability to identify nuclear material within high- and low-Z (atomic number) shielding configurations. Functional tests have been conducted using a series of customized INL Calibration Pallets. Constructed from materials spanning a range of atomic numbers and physical densities, the pallets were designed and manufactured as representative configurations for testing the PPA and other active interrogation system against shielded nuclear materials. Tests using the INL Calibration Pallets have illustrated the viability of using a photonuclear-based system to rapidly scan and identify the presence of nuclear material in a variety of cargo loading configurations. Planned enhancements to the PPA system will further increase the nuclear material detection sensitivity and will address radiation safety concerns related to field-deployment applications. These enhancements will likely include the following: (1) utilization of prompt (<1μs after the flash) radiation emissions; (2) next-generation source/accelerator design to minimize the unwanted low-energy photon dose, and (3) interrogation with higher energy (>10 MeV) photons using appropriate electron-to-photon converter dimensions.

2. Current PPA Inspection Technology

2.1. System Configuration

The current PPA inspection configuration, shown in Figures 1 and 2, was selected to facilitate the inspection of 12.2-m cargo containers while keeping the axis, defined by the detector assemblies, perpendicular to the long axis of the cargo container and offsetting the accelerator beam axis. For inspection evaluation tests, an offset angle of 42° was selected with a 250-cm standoff distance from the photon source. This configuration corresponds to the maximum possible distance from the detectors to the center of the cargo container.

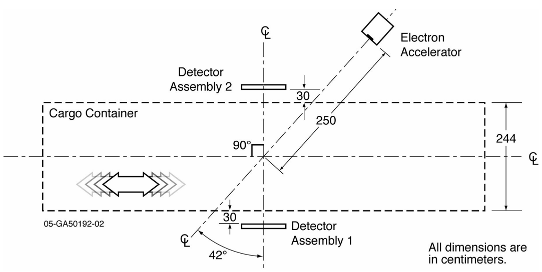

Figure 1. Plan view of PPA system configuration.

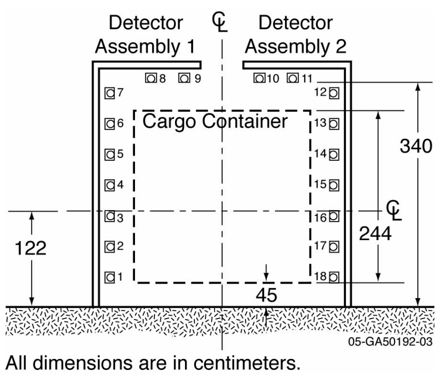

Figure 2. End view of PPA system configuration.

2.2. Theory of Operation

The PPA inspection system consists of a selectable-energy (2-12 MeV) electron accelerator - the Varitron[1], which produces 3-μs bursts of high-energy bremsstrahlung radiation. Photons having energies greater than about 6 MeV will initiate (γ,n) and (γ,f) reactions that release energetic neutrons promptly ($<10^{-12}$ s). If nuclear material is present, emitted neutrons will thermalize and further generate fission events. Additionally, delayed neutrons will be emitted from unstable neutron-rich fission products (delayed neutron precursors). If no nuclear material is present, the delayed region (> 2 ms after the photon flash) will be virtually free of energetic neutrons. Likewise, prompt and delayed gammas are also emitted during these processes and can also be exploited to indicate nuclear material.

2.3. PPA System Components

The integrated detection system acquires neutron information using an array of 18 Photonuclear Neutron Detectors (PNDs) monitoring the neutron emissions from an interrogated cargo loading. The PND is a 16-kg, 117-cm long, 10.16-cm diameter neutron detector containing an internal high voltage power supply, an INL-built preamplifier, and a 10-atm., 2.54-cm diameter, ^{3}He tube surrounded by concentric rings of polyethylene moderator, cadmium metal, and high-content, boron-loaded shielding. The combination of shielding materials with specific dimensions makes the detector sensitive to neutrons with 0.1-keV to 1.0-MeV energies and insensitive to both the ubiquitous thermal neutrons and any fast neutrons greater than ~2 MeV present after each accelerator pulse. The PND signals are compared in real-time to the actively induced, neutron background signal to determine if nuclear material is present. This neutron background is monitored with four PNDs located near the primary PND arrays, but unlike the primary array, these PNDs have their polyethylene shroud openings turned away from the cargo under interrogation. The final neutron signal monitored is the thermal neutron environment, which is measured with an unshielded, conventional ^{3}He tube of identical dimensions to those used in the PNDs. Photon radiation is monitored using unshielded, LND (Model 719) Geiger-Müller (GM) gamma-ray detectors co-located with each PND. These detectors have been selected due to their operational simplicity and their inherent interaction and recovery processes which are necessary for successful operation in a pulsed photon environment. Finally, there are 9 GM detectors (also LND 719's) operated in a proportional mode for a GSDM which gives information corresponding to the nature of the shielding located between the interrogating photon source and the transmission mapping detector array. These transmission mapping detectors are used to detect high-density (or a significant amount of low-density) shielding.

3. Detection Performance with INL Calibration Pallets

3.1. INL Calibration Pallets

Extensive testing to detect nuclear material in simulated cargo container loadings has been conducted with a set of specifically designed and constructed pallets.[4] This representative set of cargo loadings is referred to as the INL Calibration Pallets. Table 1 summarizes some key characteristics of these Calibration Pallet designs.

Table 1. Calibration Pallet Designs[5]

Pallets	Mass (kg)	Primary Material	Material Density (g/cc)
Empty	46	Aluminium	2.70
Celotex™	90	Celotex™	0.05
Borated Polyethylene	1012	5%-Borated polyethylene	1.05
Polyethylene	923	Polyethylene	0.95
Wood	482	Plywood	0.48
Lead	254	Lead	10.80
Iron	890	Iron	7.80

Calibration Pallet designs provide complete, 4π–shielding of a central void in which is placed nuclear material. The Celotex™, Borated Polyethylene, Polyethylene and Wood Pallets are rectangular in shape each measuring 1.07-m in depth, 0.86-m in width, and 1.02-m in height. The Lead and Iron Pallets are cylindrical with a radial thickness of 5.08 and 16.51 centimeters, respectively. These pallet dimensions allow them to be loaded into conventional cargo container and allow flexible, but identical, testing configurations for any interrogation technique.

3.2. Testing with the Calibration Pallets

Experimental verification of the detection capability of the PPA system has been performed using surrogate nuclear material (depleted uranium (DU)) positioned within the center of Calibration Pallets in various cargo container inspection configurations. Within the integrated acquisition system, an alarm can be generated based on either the neutron response from the PND or the photon response with the GM detectors. An alarm is triggered by the PNDs when the measured signal, from either a single detector or a grouping of three adjacent detectors, is larger than the average background neutron signal and a preset, user-specified multiple of the standard deviation of the background signal. In order to utilize photon signatures in the interrogation environment, both the gamma-ray and thermal neutron signals must be monitored. The time-dependent thermal neutron response (n_{th}) is measured and compared to the GM detector response (γ) in order to develop a time (t)-dependent Figure-of-Merit (FOM) that is mathematically evaluated after each accelerator pulse according to Equation 1.

$$\mathrm{FOM}(t) = \int_0^t \frac{\int_{t_p}^{1/\mathrm{Hz}} \gamma(t_p)\,dt_p}{\int_{t_p}^{1/\mathrm{Hz}} n_{th}(t_p)\,dt_p}\,dt$$

Equation 1. Figure of Merit calculation for GM detection algorithm.

The bulk of the gamma-ray detection is due to (n,γ) capture reactions. Accordingly, the ratio of the photon-to-thermal neutron signal is relatively insensitive to changing cargo loadings. Any additional delayed gamma-ray contribution from nuclear material, such as prompt gammas from thermal neutron fissions, or gamma-rays from the decay of delayed neutron precursors, will increase the time-dependent FOM value above a nominal FOM curve.

By utilizing these two algorithms, the nuclear material detection capability has correctly detected nuclear material in all pallet scenarios. In most pallet configurations, the detection occurs in substantially less than the typical 120-second interrogation times. Furthermore, PND and GM detector normalization techniques have eliminated false positives that had been sporadically seen in the Borated Polyethylene and Polyethylene Calibration Pallets. Early tests utilized a delayed region counting window of 1.92-7.68 ms after each accelerator pulse. Optimization of this window (currently 4-7.68 ms) has increased the signal-to-noise by approximately 10 percent. In addition, an off-axis sensitivity study illustrated that nuclear material could be detected (in selected cargo loadings) even when located up to 38 cm from the accelerator beam centerline.

4. Enhancements to Increase Fissile Material Sensitivity

4.1. Utilization of Prompt Radiation

Most active interrogation techniques including the current PPA system, have utilized the delayed neutron and gamma-ray response while largely ignoring the prompt emissions. While delayed emissions are generated on timescales of milliseconds to several seconds making them easier to distinguish from the interrogating flash, they are much less abundant than the prompt emissions. On average, only 0.0158 delayed neutrons are emitted from a thermal ^{235}U fission compared to 2.5 prompt neutrons. Exploitation of prompt radiation (defined as <u>during</u> an accelerator pulse/(photo)fission event and/or <u>immediately after (< 1 μs)</u>) has the potential to dramatically reduce interrogation times. Recent preliminary experiments (using fast plastic scintillators) conducted at the IAC suggest that it is indeed possible to extract prompt neutron emissions within a pulsed environment.

4.2. Next Generation Source/Accelerator Design

Typical Linacs produce bremsstrahlung radiation having a broadband photon energy spectrum. As the electron energy is increased, the photon flux and its corresponding forward collimation increase. Unfortunately, this comes at a price of a larger unwanted, lower energy photon component. It is interesting to note, however, that the inherent forward-collimation (with electron beam energy) only results in about a factor of two increase in the 90-degree dose at these energies. For field- deployable applications such as the PPA system, it is highly desirable to be able to produce only the usable energies within this broad spectrum while minimizing the production of undesirable, low-energy x-rays. While typical approaches focus on accelerator shielding to achieve the desired dose levels, this approach is not feasible with transportable/mobile applications. Tailoring of the photon spectrum will likely be achieved through a combination of customizing the electron source, converter target design and shielding configurations. A successfully designed, next generation accelerator would nominally be compact (~1m; <500kg), would have a converter/collimator assembly producing a narrow band of photon energies with pulses as short as one nanosecond, and would use a relatively “thin” converter thickness (with appropriate transmission electron rejection technique). Electron energies should be selectable up to 20 MeV with a high repeatability and good energy resolution.

4.3. Interrogation with Higher Energy Photons (>10 MeV)

Because of current food irradiation/inspection limitations, most active-interrogation studies with the PPA system have been performed with electron beam energies at or below 10 MeV. This is despite the fact that clinical applications using photon energies in excess of 10 MeV are already well established, with some oncology applications reaching as high as 50 MeV. While this 10-MeV energy limit currently applies to cargo inspections, the World Health Organization has indicated that higher energy electron beam operations could be considered for future operations.

Notwithstanding the current 10-MeV electron beam energy limitation, there are definite advantages to be realized with using higher photon energies for inspections. At higher photon energies, several phenomena contribute to increased shielded nuclear material detection sensitivity. Two of the most important are: (1) increased ability for source photons to penetrate shielding, and (2) enhanced (γ,n) and (γ,f) cross sections in materials, such as ^{235}U and ^{239}Pu. Numerical and experimental assessments have been conducted for various electron beam energies from 8 to 30 MeV. Increases of up to three orders of magnitude in delayed signatures have been measured over these energy ranges. Prompt emission detection would further extend detection sensitivities with potentially lower delivered cargo doses and increased throughputs.

5. Summary

The prototype PPA system is operational at INL and has demonstrated its capability to detect shielded nuclear material in representative cargo container inspection configurations. Utilizing neutron and gamma-ray detection, nuclear material has been detected in a variety of specially designed Calibration Pallets. Investigation into the exploitation of prompt fission signatures promises to unlock a prolific source of information that is currently underutilized. Highly tunable accelerators capable of producing specific energies required for photonuclear interrogation would minimize unwanted cargo and operator doses. Interrogations with energies higher than 10 MeV have the advantage of increasing the delayed neutron signal-to-noise by at least an order of magnitude.

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